FLAVOR AND SCATTERING EFFECTS IN LEPTOGENESIS

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SUSY 2011

August 31, 2011

HOW TO GENERATE A BARYON ASYMMETRY?

Sakharovs conditions (1967): SM:

- Baryon number violation ☺ (B+L)!
- CP violation 😐
- Departure from equilibrium ☹

SEE-SAW MODEL OF NEUTRINO MASSES

Minkowski 1977, Yanagida 1979, ...

- Right-handed neutrinos ψ_{Ni} are neutral singlets

- Can have Majorana mass term:

$$\mathcal{L} = \frac{1}{2}\bar{\psi}_{Ni}(\mathrm{i}\not{\partial} - M_i)\psi_{Ni} + \bar{\psi}_\ell \mathrm{i}\not{\partial}\psi_\ell - Y_i^* \bar{\psi}_\ell \phi^\dagger P_{\mathrm{R}} \psi_{Ni} - Y_i \bar{\psi}_{Ni} P_{\mathrm{L}} \phi \psi_\ell$$

- Mass matrix: $\begin{pmatrix} 0 & Y_i v \\ Y_i^* v & M_i \end{pmatrix}$

- Eigenvalues:

$$\lambda_+ \approx M_1 \qquad \lambda_- \approx |Y^2| \frac{v^2}{M_1}$$

SEE-SAW MODEL OF NEUTRINO MASSES

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new CP violation

$$\mathcal{L} = \frac{1}{2}\bar{\psi}_{Ni}(\mathrm{i}\partial\!\!\!/ - M_i)\psi_{Ni} + \bar{\psi}_\ell \mathrm{i}\partial\!\!\!/ \psi_\ell - Y_i^* \bar{\psi}_\ell \phi^\dagger P_\mathrm{R} \psi_{Ni} - Y_i \bar{\psi}_{Ni} P_\mathrm{L} \phi \psi_\ell$$

- Majorana mass violates lepton number
- Out of equilibrium decay of N_1 if couplings satisfy

$$\Gamma_{N_1} \propto \sum |Y_{1i}|^2 M_1 < H\big|_{T\approx M_1}$$

HOW TO GENERATE AN ASYMMETRY?

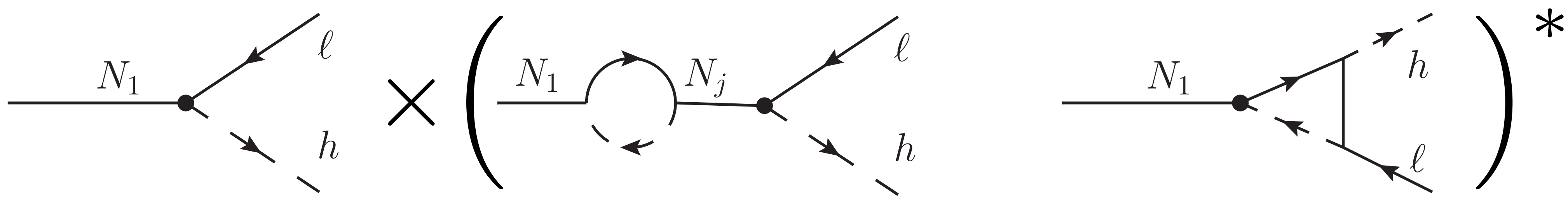
Sakharovs conditions:	SM + See Saw
Baryon number violation	☺
CP violation	☺
Departure from equilibrium	☺

Leptogenesis

Fukugita & Yanagida, 1986

USUAL WAY TO PREDICT ASYMMETRY:

- Calculate CP asymmetry in decays

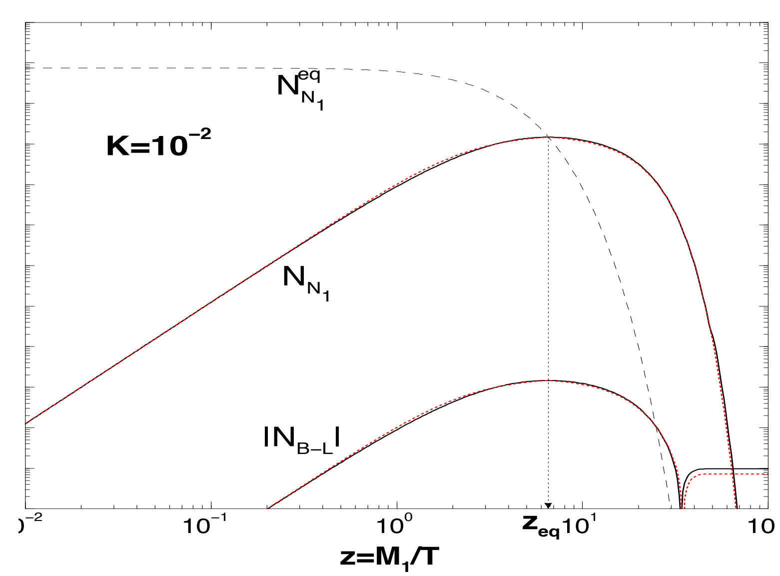


- Plug into Boltzmann equation

$$\partial_\eta f_{\ell-\bar{\ell}} = C_D[f_{\ell-\bar{\ell}}] + C_S[f_{\ell-\bar{\ell}}]$$

- Solve (with approximations)

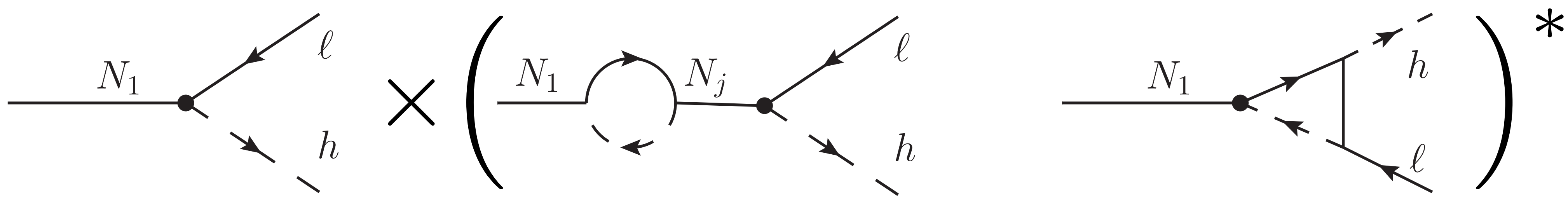
e.g. Pedestrian: Buchmuller, di Bari, Plumacher, 2000



VALID APPROACH?

- Calculate CP asymmetry in decays

Quantum Effect



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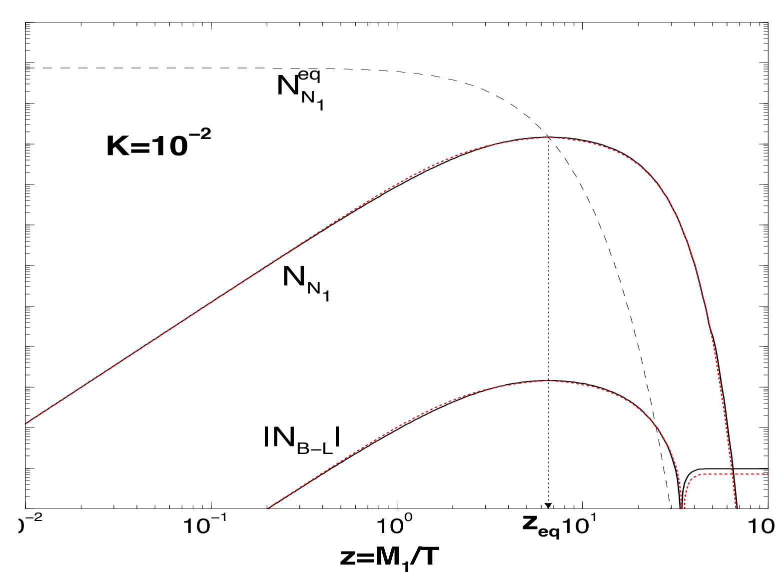
Classical Equation

$$\partial_\eta f_{\ell-\bar{\ell}} = C_D[f_{\ell-\bar{\ell}}] + C_S[f_{\ell-\bar{\ell}}]$$

- Solve (with approximations)

e.g. Pedestrian: Buchmuller, di Bari, Plumacher, 2000

something missed?



ONGOING EFFORT TO IMPROVE:

- Canonical Framework: Nonequilibrium QFT
  - Applied to Leptogenesis

    Buchmuller, Fredenhagen, 2000;
    de Simone, Riotto, 2007;
    Garny, Hohenegger, Karavtsev, Lindner, 2009, 2009;
    Anisimov, Buchmuller, Drewes, Mendizabal, 2010, 2010;
    Garny, Hohenegger, Karavtsev, 2010;
    Beneke, Garbrecht, Herranen, PS, 2010;
    Beneke, Fidler, Garbrecht, Herranen, PS 2010;
    Garbrecht, 2010;
    Beneke, Garbrecht, PS,... in progress

  - Related

    Drewes, 2010;
    Gagnon, Shaposhnikov, 2010;
    Anisimov, Besak, Bodeker, 2010;
    Herranen et al, 2011;
    Fidler et al, 2011;
    Garbrecht, Garny, 2011;

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    This talk!

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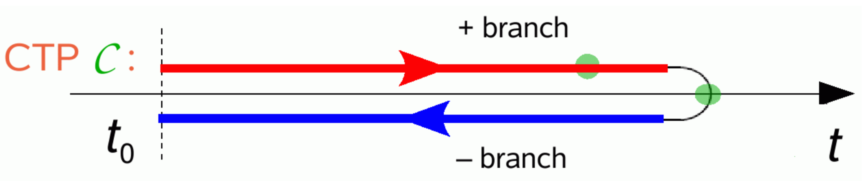
NEQFT FOR LEPTOGENESIS

- Dyson-Schwinger eqn. on CTP



$$i\partial\!\!\!/_u S^{ab}(u,v) = a\delta_{ab}\delta^4(u-v) + \sum_c \int d^4w \Sigma^{ac}(u,w) S^{cb}(w,v)$$

1PI self energies

$$iS(u,v) = \langle \psi(u)\bar{\psi}(v)\rangle$$ lepton two point function

$$\propto f_\ell(t,k)$$ lepton + antilepton densities

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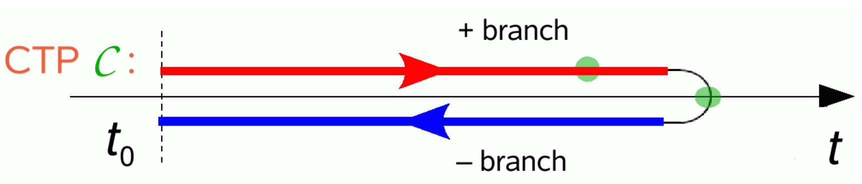

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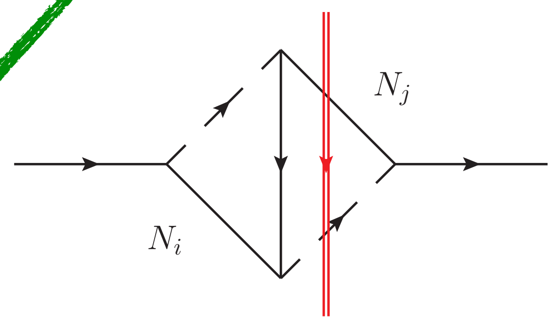


$$n_\ell(t) = \int d^3k f_\ell(t,k)$$

$$\partial_\eta(n_\ell - n_{\bar{\ell}}) = W + S$$

FINITE NUMBER DENSITY CORRECTIONS

- Source term in hierarchical limit ($M_2 \gg M_1$):

$$S = 3\,\mathrm{Im}[Y_1^2 Y_2^{*2}]\left(-\frac{M_1}{M_2}\right)\int \frac{d^3k'}{(2\pi)^3 2\,\omega_{k'}}\,\delta f_N(\mathbf{k}')\,\Sigma_{N\mu}(\mathbf{k}')\Sigma_N^\mu(\mathbf{k}')$$

$$f_N - f_N^{eq}$$

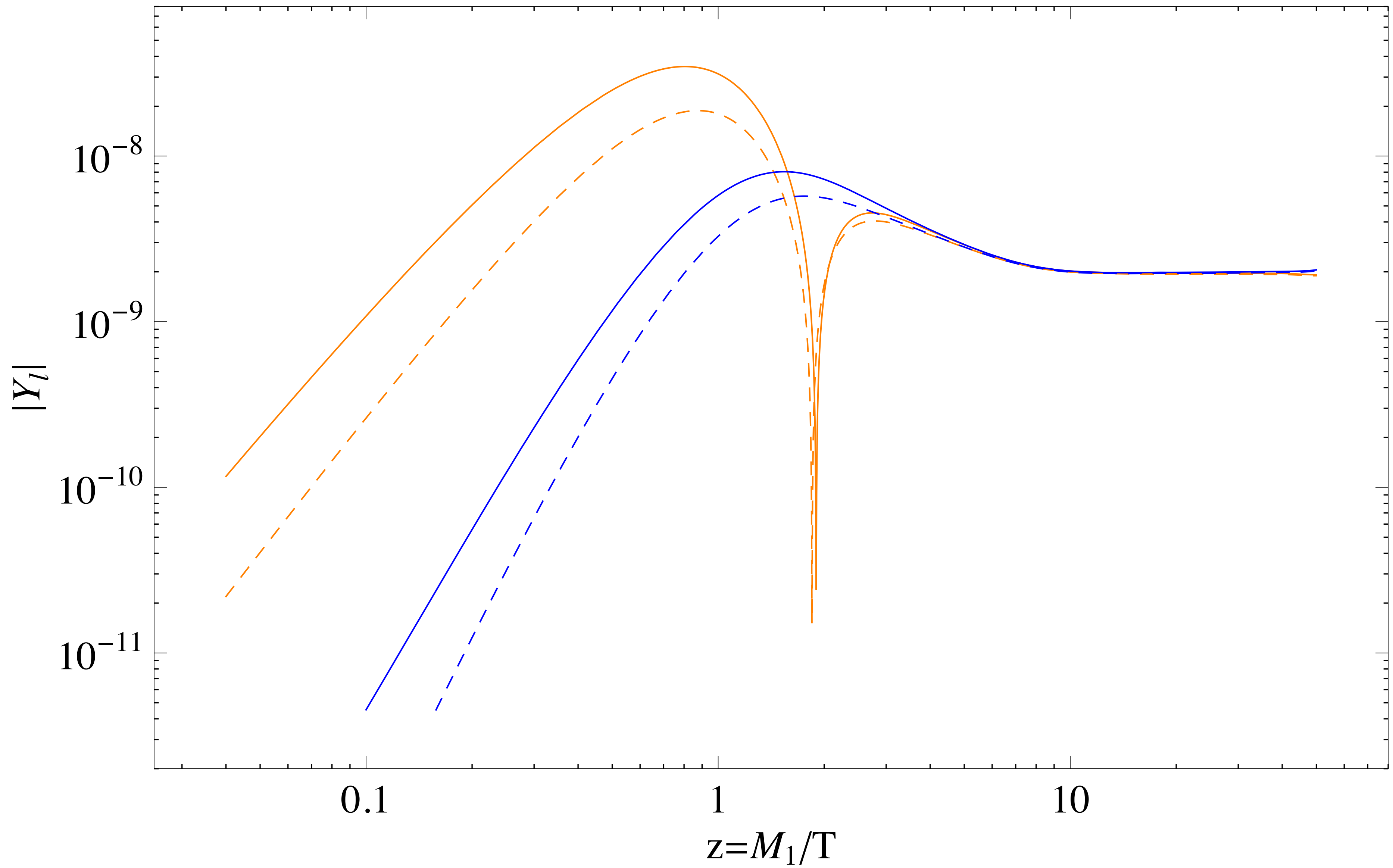
no asymmetry in equilibrium

$$\Sigma_N^\mu(k) = \int_{p,q} \delta^4(k-p-q)\,p^\mu\left(1 - f_\ell^{\mathrm{eq}}(\mathbf{p}) + f_\phi^{\mathrm{eq}}(\mathbf{q})\right)$$

finite density corrections

In vacuum QFT: $\Sigma_N^\mu(k) = \dfrac{k^\mu}{16\pi}$

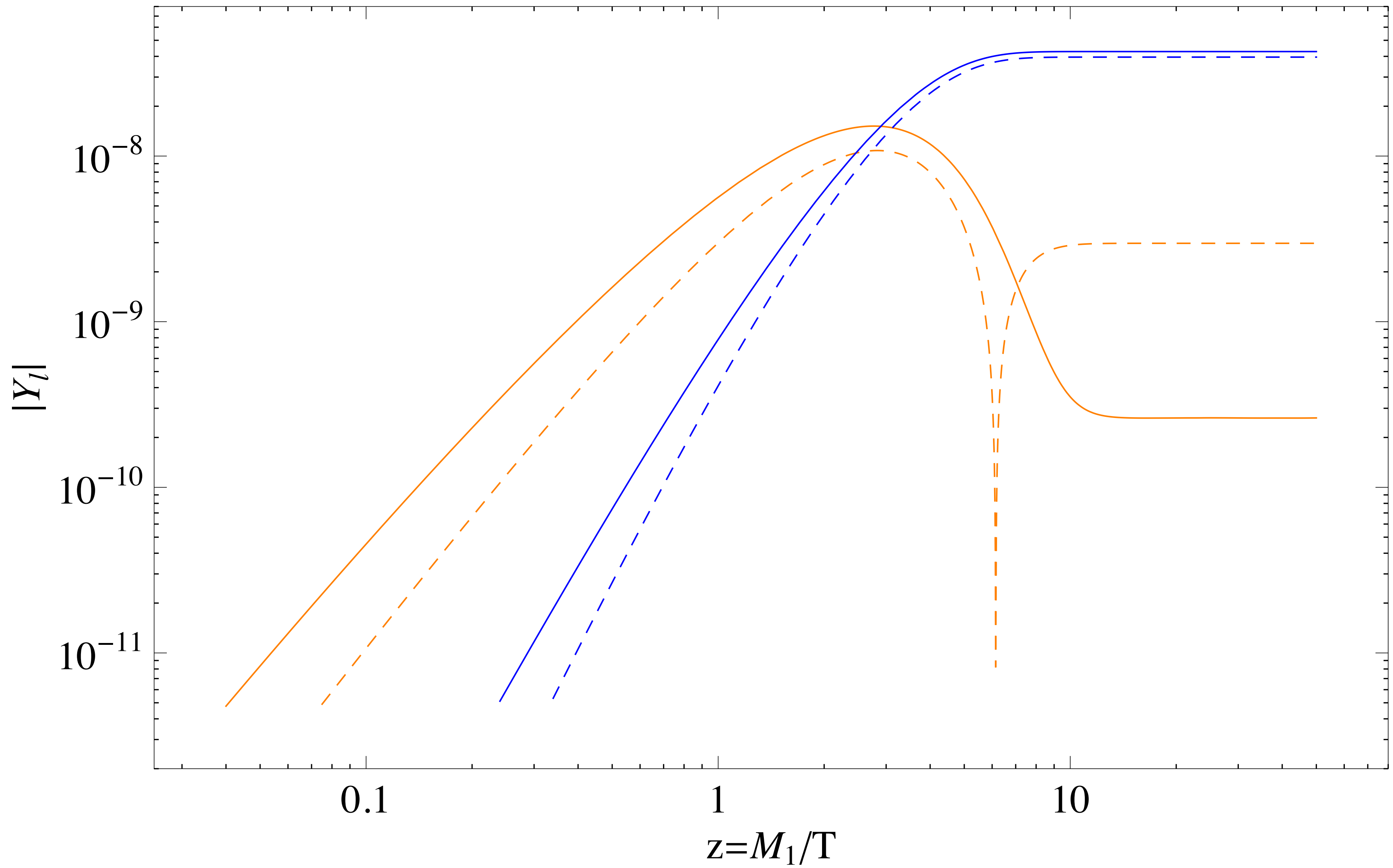
THERMAL EFFECTS: STRONG WASHOUT



blue: thermal initial N_1 density

red: zero initial N_1 density

THERMAL EFFECTS: WEAK WASHOUT



can be sizable!

blue: thermal initial N_1 density
red: zero initial N_1 density

LEPTON FLAVORS

Barbieri et al, 2000; Endoh et al, 2004; Abada et al, 2006; Nardi et al, 2006;

- Neutral and charged Lepton Yukawa couplings in general not aligned

$$\mathcal{L} = Y_{ia}\bar{\psi}_{Ni}\phi\psi_{\ell a} + h_{ab}\bar{\psi}_{Ra}\phi^{\dagger}\tau\psi_{\ell b} + \mathrm{h.c.}$$

- Leptogenesis usually dominated by N_1 decays

- Decay into linear combination of e, μ, τ

$$N_1 \to \phi\ell\,, \qquad \ell \sim \alpha_e \ell_e + \alpha_\mu \ell_\mu + \alpha_\tau \ell_\tau$$

MODIFICATION OF WASHOUT RATES

- Assume tau Yukawa in thermal equilibrium
- ℓ Projected onto states ℓ_τ and $\ell_\perp$ by flavor sensitive interactions (denote as $\ell_{1,2}$)
- Boltzmann E: $$\frac{d}{d\eta}\Delta n_{\ell i} = W_i + S_\ell$$
- Small washout in one flavor can largely increase the asymmetry (over 100%)

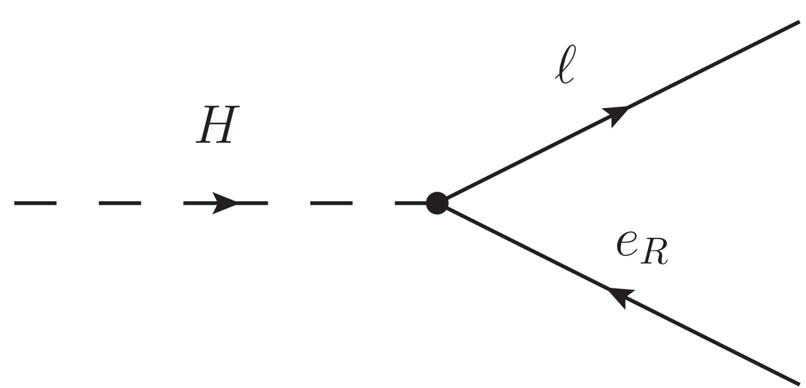
FLAVORED EVOLUTION EQUATIONS

Beneke, Fidler, Garbrecht, Herranen, PS, 2010

$$\frac{\partial q_\ell}{\partial \eta} = -[\Xi, q_\ell] - \{W, q_\ell\} + 2S - \Gamma_\ell^{\text{fl}}$$

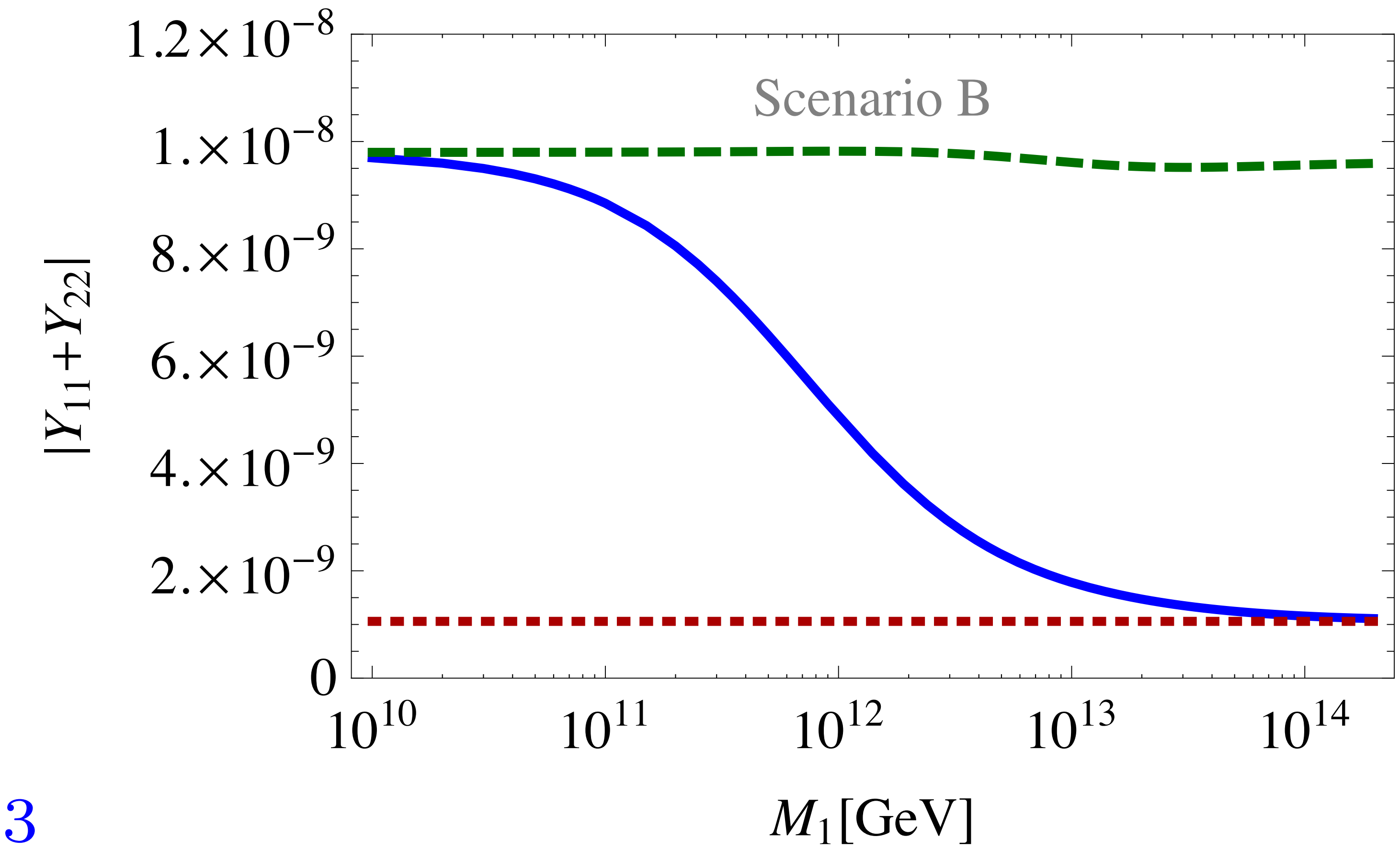
- No oscillation term: suppressed by fast flavor-insensitive gauge interactions

- Decoherence only through flavor sensitive scatterings



IMPORTANCE OF FLAVOR

- Total asymmetry as function of the Leptogenesis scale



- Unflavored: $M_1 > 10^{13}$

- Fully Flavored: $M_1 < 10^{11}$

blue: full solution
red: unflavored
green: fully flavored

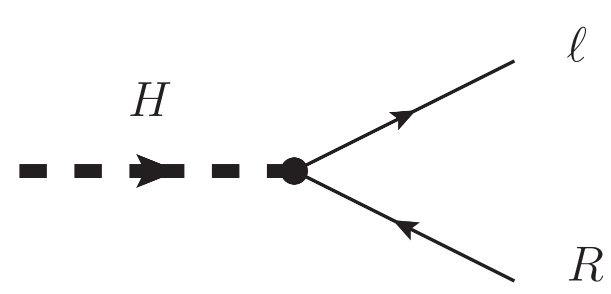
YUKAWA INTERACTION RATES

- Responsible for
  - N1 production/decay -> strength of washout
  - Flavor sensitive scatterings -> scale where different flavor regimes are valid
- Difficulty
  - massless 1->2 processes zero at tree level $\mathcal{O}(g^2T)$
  - massive 1->2 affected by thermal masses $\mathcal{O}(g^2T)$
  - properly include all contributions at $\mathcal{O}(g^2T)$

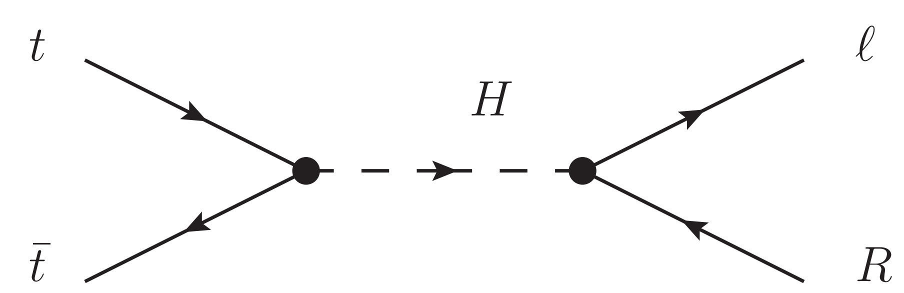
LEADING CONTRIBUTIONS

- Thermal masses/width

thermal masses:
Giudice, Notari, Raidal, Riotto, Strumia, 2003;
Kiessig, Plumacher, Thoma, 2009;

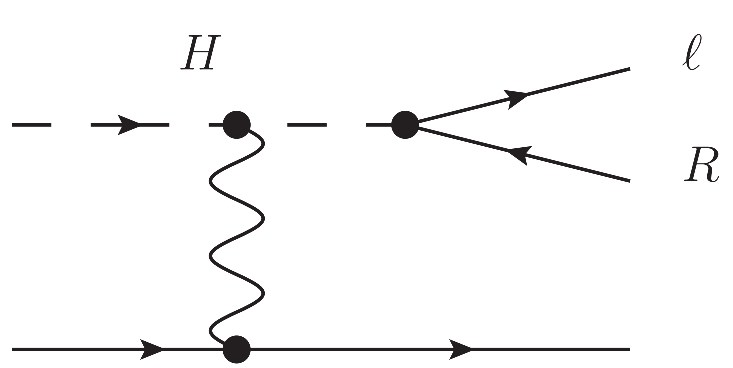


- Off-shell $2 \rightarrow 2$ scatterings



- Collinearly enhanced $2 \rightarrow 3$ processes

Arnold, Moore, Yaffe, 2000;
Anisimov, Besak, Bodeker, 2010;



APPROACH

- Use 2PI vacuum diagrams to obtain 1PI self energies
- resums bubble subgraphs (not 2PI) into propagators
- avoids divergencies in t channel diagrams
- 2->3 following AMY, ABB
  - currently checking results, numerics. Soon!

CONCLUSIONS

- Ongoing effort to understand Leptogenesis at the quantum level
- Consistent framework to derive evolution equations for lepton asymmetry
- Solid formalism for calculating interaction rates
- Dynamics of important early universe process from first principles

BACKUP!

SUPPRESSION OF OSCILLATIONS

- Flavor blind interactions $\Gamma^{\rm bl} \sim g_2^4\, T$ $\left(\begin{array}{c}\text{kinetic}\\ \text{equilibrium}\end{array}\right)$
- Oscillations $\Delta\omega \sim h_\tau^2\, T << \Gamma^{\rm bl}$ $\left(\begin{array}{c}\text{from thermal}\\ \text{masses}\end{array}\right)$
- Toy Model:

$$d(\delta^+)/dt = -\mathrm{i}\omega\,\delta^+ - \Gamma^{\rm bl}[\delta^+ + \delta^-]$$
$$d(\delta^-)/dt = +\mathrm{i}\omega\,\delta^- - \Gamma^{\rm bl}[\delta^+ + \delta^-]$$

- Last term enforces $\delta^+ = -\delta^- + \mathcal{O}(\omega/\Gamma^{\rm bl})\delta^-$
- Oscillations suppressed by large $\Gamma^{\rm bl}$

DEPENDENCE ON LEPTOGENESIS SCALE

- Expansion of Universe:

$$H = 1.66\sqrt{g_\star}\frac{T^2}{M_{\rm pl}}$$

- Charged Higgs Yukawa interactions:

$$\Gamma^{\rm fl} \propto h_\tau^2 T$$

- Tau Yukawa in equilibrium below 10^{12} GeV
- If Leptogenesis takes place at or below this scale, flavor is important

FULLY FLAVORED REGIME

Abada et al, 2006
Nardi et al, 2006

- Two flavor regime $T < 10^{12}$ GeV
  and three flavor regime $T < 10^{9}$ GeV

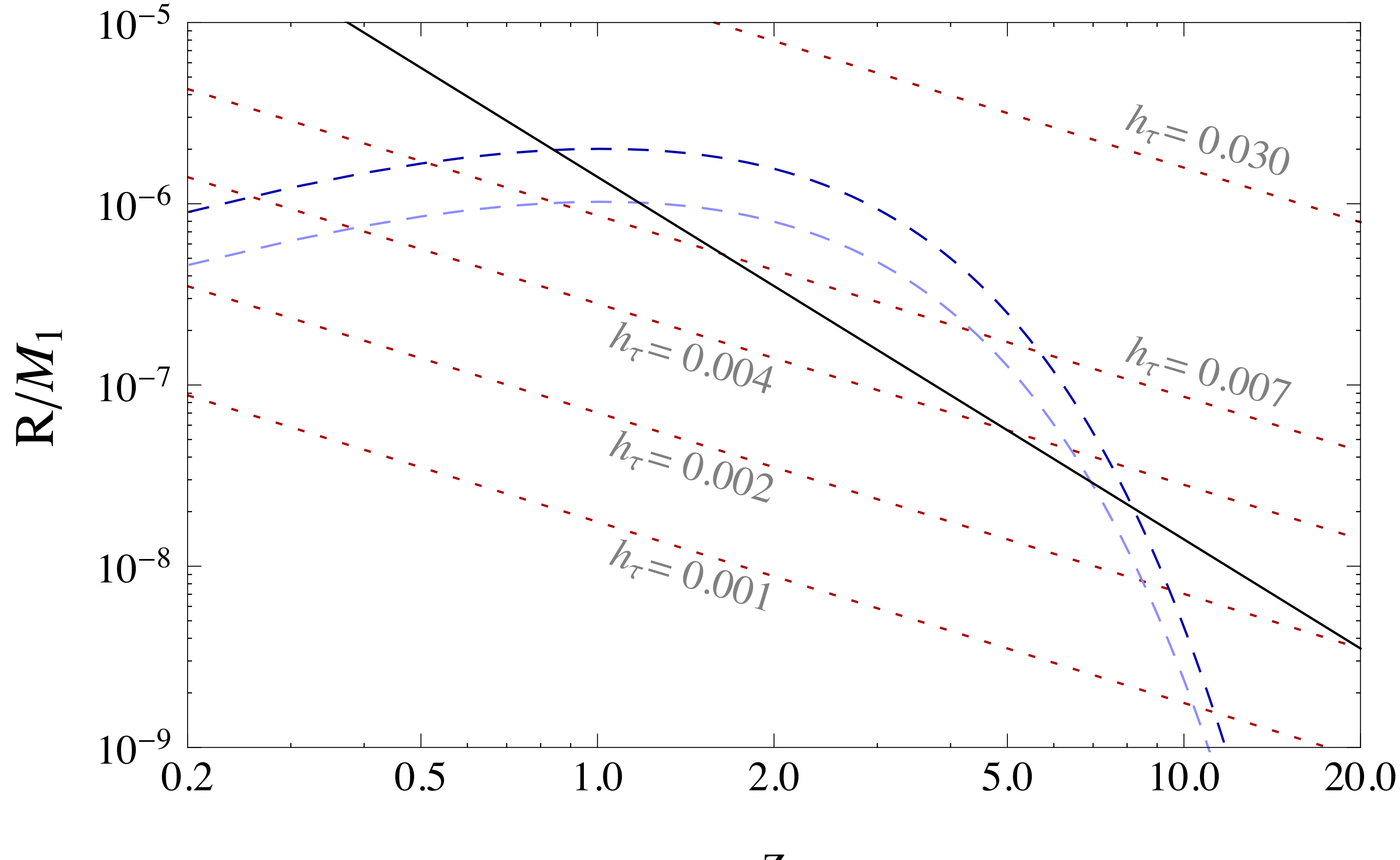
- Work in charged lepton mass basis, calculate separate washout and source terms for each flavor

$$\frac{d}{d\eta}\Delta n_{\ell i} = W_i + S_i + \ldots$$

- Flavor oscillations?

INTERMEDIATE REGIME

- Washout, expansion, flavor decoherence with similar strength



- Separate treatment of flavors not sufficient

- ideally: find basis invariant formalism

OUR APPROACH

Beneke, Garbrecht, Herranen, PS, 2010

- Derive evolution equations for number densities directly from Nonequilibrium Quantum Field Theory
- Natural basis for treatment of flavor
- Obtain finite temperature/density corrections to CP asymmetries
- Automatic implementation of real intermediate state subtraction (no double counting)

NONEQUILIBRIUM QFT

- Conventional QFT: Calculate “in - out” correlators (S-matrix elements)

$$_{\mathrm{in}}\langle A|B\rangle_{\mathrm{out}} = \langle A|U(-t,t)|B\rangle_{t\to\infty} = \langle A|S|B\rangle$$

- NEQFT: Know the “in” state $\rho(t_0)$, want to predict the time evolution of operator:

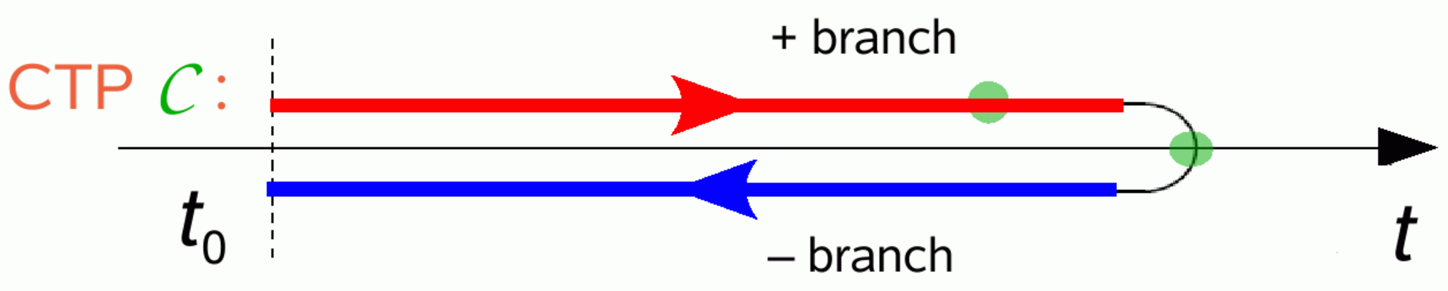
$$\langle t|\mathcal{O}|t\rangle = \mathrm{Tr}[\rho(t_0)U^\dagger(t,t_0)\mathcal{O}U(t,t_0)]$$

CTP FORMALISM

Schwinger, 1961; Keldysh, 1964, ...

- Instead of "in-out" correlators: Calculate "in-in" expectation values

- Possible using conventional QFT methods if we let time coordinate on Closed Time Path



- Fields get additional index $\phi^a(t,x)$ that indicates the position of the time coordinate $a = \pm$

CTP FORMALISM

- Relevant information contained in 2-point functions for bosons $\Delta(u,v)$ and fermions $S(u,v)$
- become 2x2 matrices $\begin{pmatrix} G^{++} & G^{+-} \\ G^{-+} & G^{--} \end{pmatrix} = \begin{pmatrix} G^{T} & G^{<} \\ G^{>} & G^{\bar{T}} \end{pmatrix}$
- Time evolution from Dyson-Schwinger equation:

$$i\not{\partial}_u S^{ab}(u,v) = a\delta_{ab}\delta^4(u-v) + \sum_c \int d^4w \Sigma^{ac}(u,w) S^{cb}(w,v)$$

1PI self energy

QUANTUM BOLTZMANN EQUATIONS

- Gradient & loop expansion, quasiparticle approximation (also, a Wigner transformation in between)
  - Obtain evolution equations for number densities

$$\frac{d}{d\eta} f_{N1}(\mathbf{k}) = D(\mathbf{k})$$
$$\frac{d}{d\eta}(n_\ell - \bar{n}_\ell) = W + S\,.$$

  - Conformal time η to incorporate expansion of the universe, proportional to inverse temperature

NOW WITH FLAVOR

Beneke, Fidler, Garbrecht, Herranen, PS 2010

- just "add" flavor indices to field operators

$$iS_\ell^<(u,v) = \langle \bar{\psi}_\ell(v)\psi_\ell(u)\rangle$$

$$\longrightarrow \qquad iS_{\ell ab}^<(u,v) = \langle \bar{\psi}_{\ell b}(v)\psi_{\ell a}(u)\rangle$$

- Straightforward generalization for washout and source terms

- In addition: oscillations, flavor sensitive scatterings

FLAVOR OSCILLATIONS

- Commutator term in kinetic equation:

$$i\partial_\eta S_\ell^{<,>} - \left[\mathbf{k}\cdot\gamma + \not{\Sigma}_\ell^H, S_\ell^{<,>}\right] = -\frac{1}{2}\left(\mathcal{C}_\ell + \mathcal{C}_\ell^\dagger\right)$$

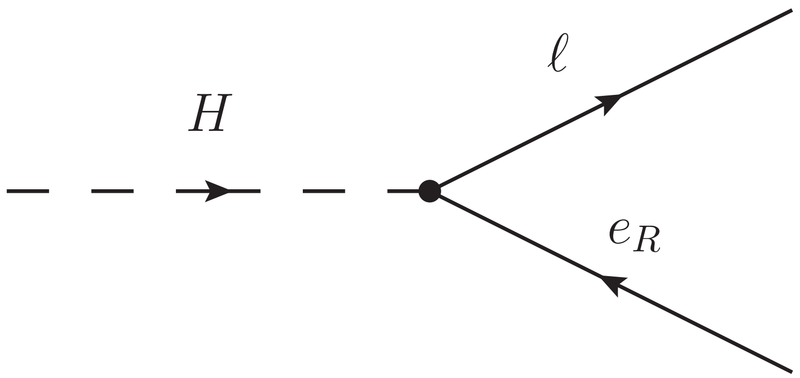
- Time dependent mass basis, diagonalize self energy using $\Sigma_D^H = U^\dagger(\eta)\Sigma^H U(\eta)$

- additional term $\mathrm{i}\left[\Xi, S_\ell^{<,>}\right]$ with $\Xi = U^\dagger \partial_\eta U$

$$\partial_\eta \delta n_{\ell ab}^{\pm} - \left[\Xi, \delta n_\ell^{\pm}\right]_{ab} \pm \mathrm{i}\Delta\omega_{ab}\delta n_{\ell ab}^{\pm} = \pm\frac{1}{2}\left(C_\ell + C_\ell^\dagger\right)_{ab}$$

FLAVOR SENSITIVE INTERACTIONS

- Main source of flavor decoherence
- Contributions from annihilation/scatterings



- all processes allowed at finite temperature
- estimate using $\Gamma^{\mathrm{an}} + \Gamma^{\mathrm{sc}} \approx 0.7\,\alpha_w\,T$

FLAVORED EVOLUTION EQUATION

- Gauge interactions enforce kinetic equilibrium also for off diagonal densities

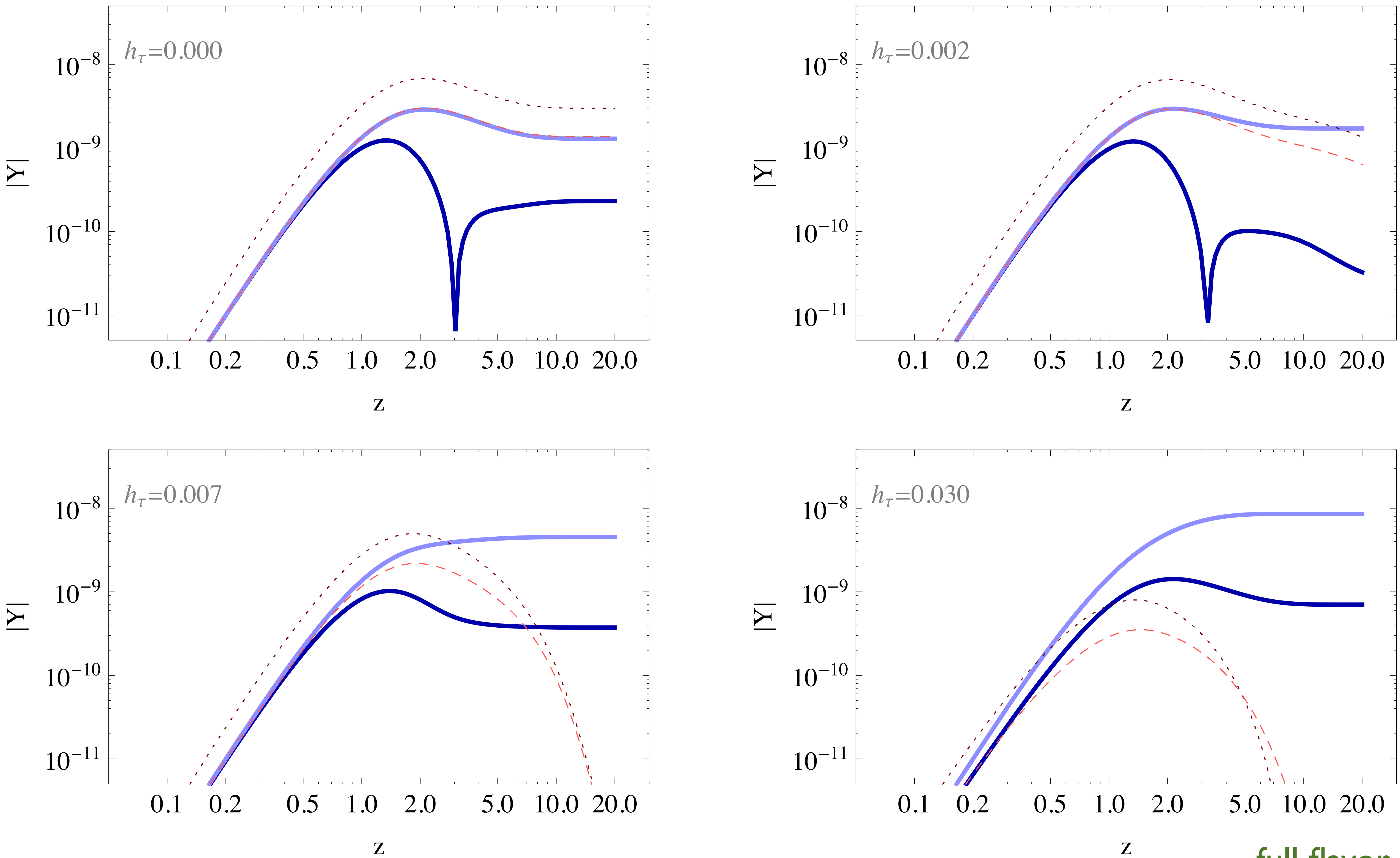
- Introduce flavored number densities $n^{\pm}_{\ell ab}$, define flavored charge density $q_{\ell ab} = n^{+}_{\ell ab} - n^{-}_{\ell ab}$

- **Evolution equation:**

$$\frac{\partial q_\ell}{\partial \eta} = -\left[\Xi, q_\ell\right] - \{W, q_\ell\} + 2S - \Gamma^{\text{fl}}_\ell$$

NUMERICS (CHARGED LEPTON FLAVOR BASIS)

no flavor



full flavor

WHEN ARE FLAVOR EFFECTS IMPORTANT?

- Three regimes (neglecting muon, electron Yukawas and assuming that flavors are not aligned)
- Unflavored: Single flavor approximation is good
- Fully Flavored: Off-diagonal densities can be neglected
- Intermediate: Full evolution equation needs to be solved

BARYON NUMBER VIOLATION

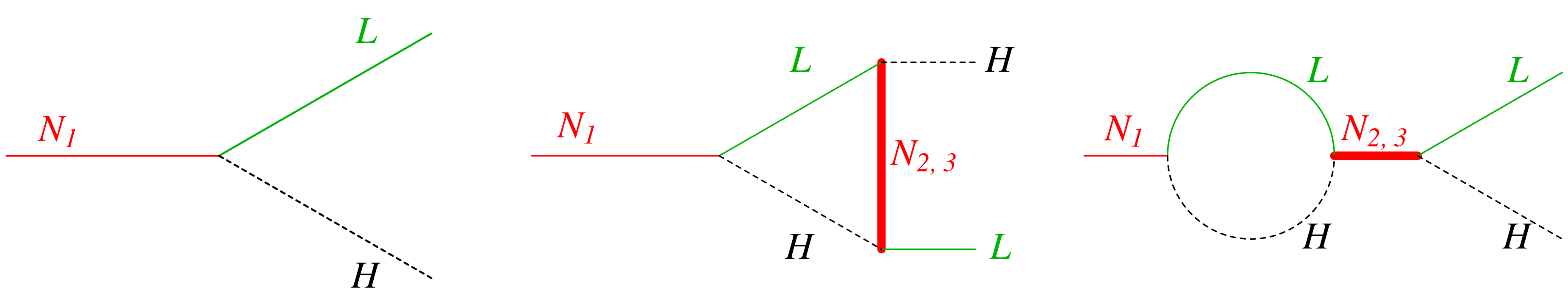
- Early universe has zero baryon number, but todays universe has a nonzero B
- Lepton number L violated by Majorana mass term
- Electroweak sphalerons can convert the lepton asymmetry into a baryon asymmetry

$\longrightarrow$ Generating a lepton asymmetry sufficient

CP VIOLATION

- Must be able to distinguish particles from anti-particles

- In Leptogenesis: CP violated in decays of heavy right-handed neutrinos:



CP VIOLATION II

- QM: Observables are expectation values of operators

$$\Gamma(N_1 \to H\ell^+) = |\langle N_1|\mathcal{H}_{\rm int}|H\ell^+\rangle|^2 = |\mathcal{A}|^2$$

- Asymmetry: $$Y_L = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

- Simplest case: $$\mathcal{A} = h_1 A_0$$ $$\bar{\mathcal{A}} = h_1^* A_0$$

No asymmetry since $\bar{\Gamma} = \Gamma$

CP VIOLATION III

- Add one loop correction

$$\mathcal{A} = h_1 A_0 + h_1^* (h_2)^2 A_1$$
$$\bar{\mathcal{A}} = h_1^* A_0 + h_1 (h_2^*)^2 A_1$$

- Asymmetry proportional to interference term

$$Y_L \propto \Im(h_1 h_1 h_2^* h_2^*) \Im(A_0 A_1)$$

- Note: Requires complex couplings and complex A_1

IN LEPTOGENESIS

- In early universe: Expansion with Hubble rate

$$H = 1.66\sqrt{g_\star}\frac{T^2}{M_{\rm pl}}$$

- Processes with rates $\Gamma \lesssim H$ go out of EQ
- Distributions $f(k,t)$ deviate from $f^{eq}(k) = \dfrac{1}{e^{\beta E(k)} \mp 1}$

CONFORMAL TIME STUFF

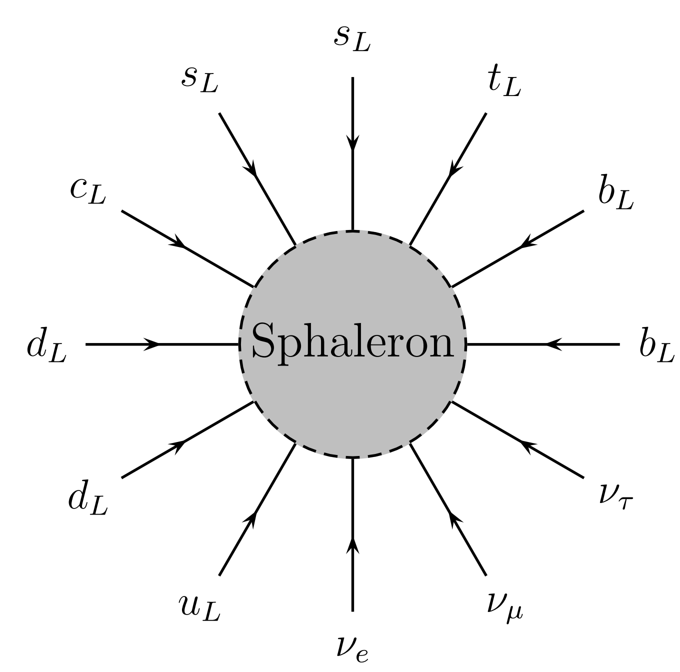
- Temperature:

$$T = \frac{T_{\rm com}}{a(\eta)} = \frac{1}{a(\eta)}\sqrt{\frac{a_{\rm R} m_{\rm Pl}}{2}}\left(\frac{45}{g_* \pi^3}\right)^{1/4}$$

- Expansion rate (radiation dominated): $a(\eta) = a_R \eta$
- "time variable" $z = M_1/T \propto \eta$
- Time derivative becomes $\frac{d}{d\eta} = a_R \frac{d}{dz}$

THE ELECTROWEAK SPHALERON

- $B+L$ current is anomalous in the SM
- At $T=0$: Tunneling between configurations with different $B+L$ highly suppressed
- At $T \gtrsim \mathrm{TeV}$: In equilibrium
- have $\Delta B = \Delta L = 3$: no proton decay



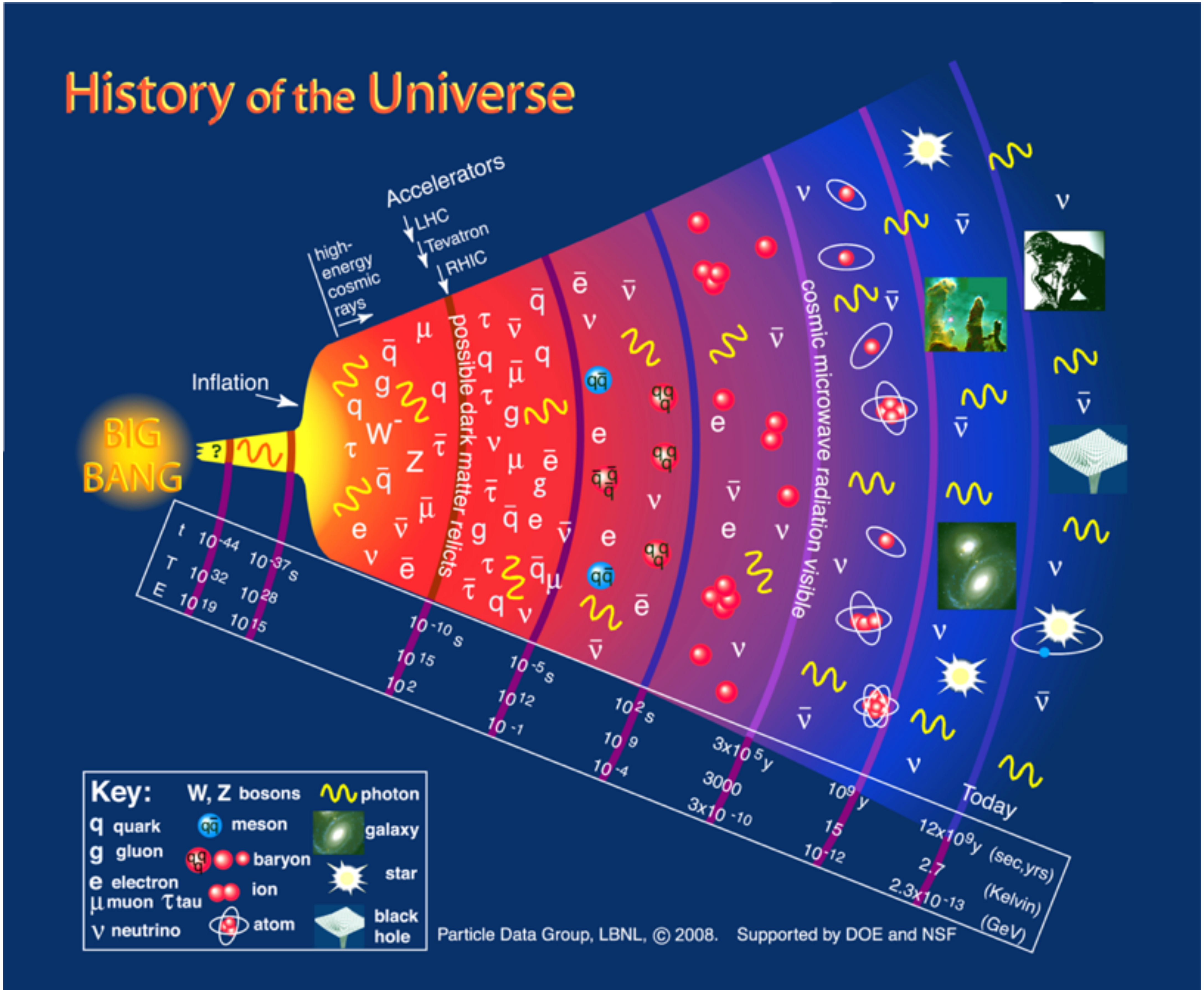
THE BARYON ASYMMETRY

- The number we have to explain is

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

- Entropy $s = g_\star (2\pi^2/45) T^3$ is conserved, related to photon density: $s = 7.04\, n_\gamma$

- Measured using BBN (deuterium abundance) and CMB anisotropies (temperature fluctuations)


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relics
cosmic microwave radiation visible
Today
t 10-44 10-37s 10-10 s 10-5 s 102 s 3x10 5 y 109 y 12x109 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 102 10 -1 10 -4 3x10 -10 10-12 2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
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